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Transmission alternatives for offshore electrical power

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ABSTRACT

The oceans represent a huge energy reservoir. Although today all of the marine power projects are very near from the shore and they are rated at low power, the huge potential of the seas may in a not very distant future bring marine power further into the sea. Also offshore oil and gas exploration is moving into deeper waters and at longer distances from land. New carbon sequestration projects under the seabed are on the way which require a vast amount of electric power consumption. The substitution of offshore power generators by power provided from the grid may have environmental benefits, but the deployment of offshore transmission of bulk electrical power to or from offshore platforms to the electrical grid onshore is a mayor challenge. The main objective of this paper is to focus on trends that can lead to a feasible transmission system in offshore energy systems far from land, and to introduce the technological alternatives which could help to reach that goal. The paper describes the main alternatives and the technical and economical aspects of the transmission of electrical power offshore.

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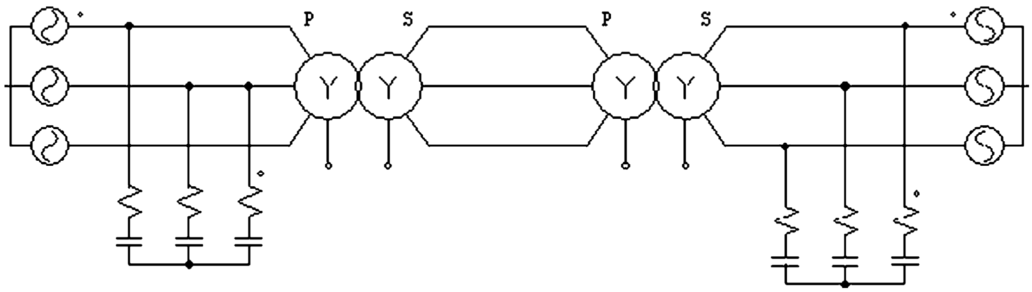

Fig. 1. HVAC transmission system.

1. Introduction

The electrical power demand of offshore platforms for oil, gas and carbon sequestration[1] is usually provided by inefficient gas turbines with high emissions of CO_2. A considerable reduction in CO_2 emissions is obtained when electrical compressors with power delivered from the onshore electrical grid are used. A first attempt at reducing CO_2 emissions at offshore platforms by this method is the Troll Gas station. The platform avoided annual emissions of 230,000 tons of CO_2 and 230 tons of NO_X, equivalent to the pollution from 75,000 cars by replacing gas generators by an offshore electrical power transmission system connected to the onshore grid [1].

Oil and gas is not the only power source in the oceans. Marine power is a vast resource that could play a leading role in the future for the energy needs of the world [2,3]. Development of systems for the extraction of power from sea currents (Seagen, Seaflow, Stingray, TidEL, ...), marine thermal power and wave energy (Pelamis, AWS, Wave dragon, Wave plane, OPT, WaveGen, Sperboy, ...) are under way. All of these projects are located very near from the shore and most of them are rated at low power. High power marine power farms are not projected far from the shore in spite of the huge potential. The main difficulty is the placement of all necessary equipment (transformers, power converters, switch gear, etc.) either floating or underwater at very deep waters and the installation of submarine cable to carry the power to the consumers onshore. This paper tries to explain the advantages and disadvantages of the most likely offshore transmission systems and it will focus in high power transmission. The existing transmission alternatives, HVAC, HVDC line commutated converter (LCC) and HVDC voltage source converter (VSC), high voltage or medium voltage, necessary auxiliary equipment, cable technology, etc. are described. All this diversity is further increased because no two identical installations are possible due to the different currents, meteorology, transmission distance, seabed soil, maritime traffic and other factors.

The power demand of big offshore oil and gas fields and high power marine power farms will be formed by a cluster of electrical compressors or generators and all the power should be sent to the grid through high voltage cables to an onshore substation connected to the grid. Development of offshore power transmission should gain from previous experience in offshore wind farms and gas and oil extracting platforms. Oil and gas extracting platforms need electrical power supply for the operation of their machinery, mainly compressors. Today these platforms use mainly, depending on power and distance, medium or high voltage (10–100 kV) ac transmission. There is a great variation in the power demand in oil and gas platforms. The factors affecting the power of the platform are the oil or gas field size, need for compression and gas or water injection, temperature, oil or gas transport system, etc. Today power of 10–100 MW is needed in small fields and power above 100 MW is used in big gas and oil fields such us Ekofisk or Tampen of 500 MW [4]. Oil and gas fields located with a depth of up to 3.166 m exist (BP's Stones 1 Walker Ridge Oil field) [5]. Besides HVAC transmission, HVDC transmission has also been used in at least one gas field in the North Sea. Since 2005 the compressor in the Troll platform is powered by a HVDC system of $\pm$60 kV, with a transmission distance of 70 km and a power rating of 84 MW. Onshore the system is connected to the 132 kV transmission grid and, in the offshore platform, the isolated grid has a voltage of 56 kV. The main difference between the oil and gas industry and marine power is the benefit margin. Costs differences that are negligible in the oil and gas industry may be the difference between success or failure in a marine power project.

Another important factor in the development of marine power is the depth of the seabed. Floating platforms can be installed in locations with very deep seabed but the technology for the installation of submarine cable can reach about 1000 m. The experience in oil and gas exploration at 3000 m seabed should be very valuable for the expansion of marine power generation.

2. Marine transmission systems

Three different alternatives exist to achieve offshore electrical power transmission: HVAC, HVDC LCC and HVDC VSC. A different approach is discussed in Section 2.4.

2.1. HVAC

Most of the existing offshore transmission systems use HVAC for the transport of electrical power between mainland and stations located on (or under) the sea. It is a well established technology. An HVAC system contains the following main components (Fig. 1):

- ac collecting system in the platform.
- Offshore transforming substation with transformers and reactive power compensation.
- Three-phase submarine cable (generally XLPE three-core cable).
- Onshore transforming substation with transformers and reactive power compensation.

The collector system depends on the generator technology. For short distances (a few kilometers), if the collector voltage is high enough (33 kV) the offshore transforming substation may not be necessary, but if the transmitted power or the transmission distance is long, the number of cables and the losses are too high and a raise in the transmission voltage is necessary. Horns Rev,

[1] In 1991 the Norwegian authorities introduced a CO_2 offshore tax with the aim of reducing CO_2 emissions. Motivated by this tax, Statoil proposed to remove the CO_2 offshore and inject it into a deep geological layer below the Sleipner platform, 250 km from land.

Table 1
Marine HVAC installations

Project	Power (MW)	Transmission system (km)	Voltage (kV)
Abu Safah Oil Field (Saudi Arabia)	52	50	115
Horns Rev Wind Farm (Denmark)	160	21	170
Samsö Wind Farm (Denmark)	20	7.6	36
Nysted Wind Farm (Denmark)	165	55	132
Q7 Wind Farm (The Netherlands)	120	28	170
Lillegrund Wind Farm (Sweden)	110	33	145
Burbo Banks (United kingdom)	90	40	36
Utgrunden Wind Farm (Sweden)	10	11	24

with a power of 160 MW and a transmission distance of 21 km, has been the first offshore wind farm using HVAC.

When the voltage of the transmission line and the grid voltage are equal the transformer is not neccesary. For example, the Cape Wind offshore wind farm uses a 115 kV marine transmission line to make the connection with the 115 kV grid onshore, thus a transformer is not neccesary.

Due to their construction, distributed capacitance in submarine cables is much higher then the capacitance in overhead lines. Thus the transmission length is reduced for marine applications. Reactive power increases with voltage and length of the cable and long-transmission distances require big reactive compensation equipment at both ends of the line. Some existing oil, gas and wind farms using HVAC transmission are shown in Table 1.

2.2. HVDC LCC

A HVDC LCC or classical HVDC system is based on LCCs using thyristors as the switching element [7]. The origin of the name of the converter is the need of an existing ac network in order to achieve proper commutation. This converter operates with switching frequencies of 50–60 Hz and the power losses are 1–2%. This kind of transmission system can only transfer power between two (or more) active grids and an auxiliary start-up system would be necessary in the offshore marine farm. Fig. 2 shows an schematic of a 12-pulse HVDC LCC transmission line. HVDC systems allow for instantaneous power control and there is no limit in the transmission distance unlike HVAC.

The first HVDC LCC system with submarine cable was built in Sweden in 1954 between the island of Gotland and mainland Sweden with a 100 kV submarine cable and with a transmission system of 96 km. Application of HVDC LCC submarine transmission has only been used for connection of high voltage grids and there is no single converter station located in the sea. There is no single HVDC LCC system for the connection of offshore wind farms, gas or oil extracting platforms. Anyway several universities and firms are studying the viability of HVDC LCC in this applications [8,9]. In Table 2 some existing installations are shown.

Table 2
Marine HVDC LCC installations

Project	Power (MW)	Transmission system (km)	Voltage (kV)
Basslink (Australia–Tasmania)	500	290	400
Italy–Greece HVDC link	500	163	400

HVDC LCC systems have the following main components at each end of the transmission line:

- Transformers.
- LCC power converter based on thyristors.
- ac and dc filters.
- dc current filtering reactance.
- Capacitors or STATCOM for reactive power compensation.
- dc cable.

The main characteristics of the components are

- *Transformers*. Substations at both ends need transformers in order to raise the voltage to the necessary level for the transmission line. Usually both star and delta connections are required for a 12-pulse converter (see Fig. 2). 12-Pulse converter cancel harmonics and the filter size is reduced. HVDC LCC transformer design is challenging because they must provide isolation at the ac plus dc voltages and tappings must be included for the proper control of the system [7].
- *LCC power converter based on thyristors*. The LCC power converter is the heart of a HVDC LCC system because it is the element that obtains the ac to dc conversion and vice versa. Today thyristors with silicon waffers of 125 mm exist capable of standing 8 kV and currents up to 4 kA dc. HVDC LCC systems of 1000 MW onshore and 500 MW offshore are feasible with state of the art technology. LCC converters need reactive power for proper operation because the current is out of phase with the line voltage due to the control angle of the thyristors. Also the reactance of the line and the transformers affect the control characteristics of the system and Constant Extinction Angle control is necessary [7].
- *ac and dc filters*. LCC converters generate a high content of low order harmonics in the line currents and ac and dc filters are necessary. These ac filters supply part of the reactive power

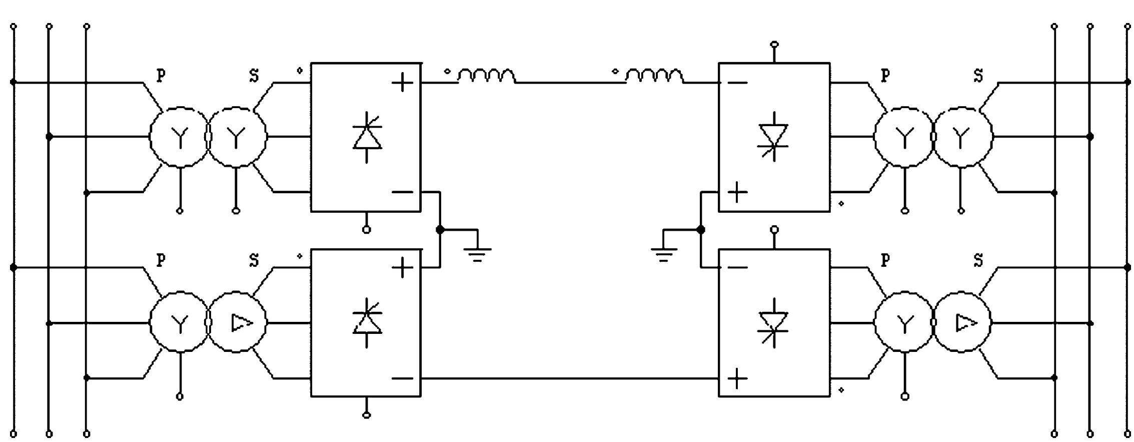

Fig. 2. HVDC LCC transmission system.

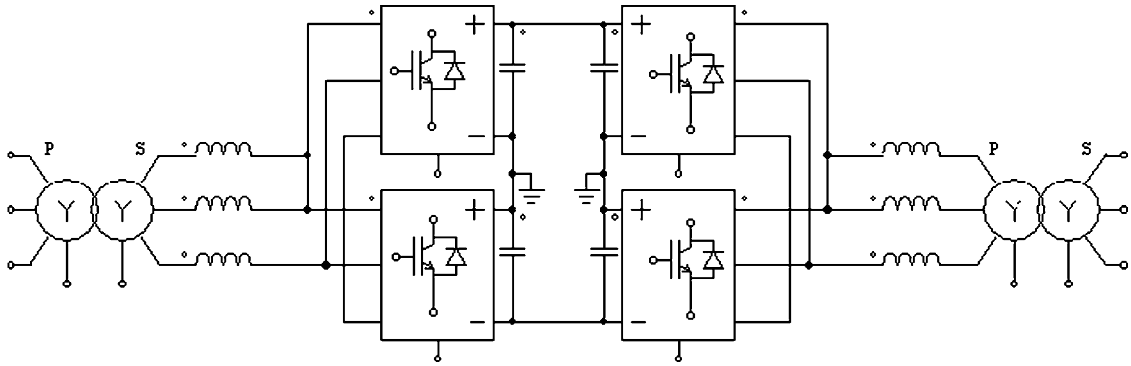

Fig. 3. HVDC VSC transmission system.

needed by the LCC converter as well. The dc filter avoid the generation of circulating ac currents in the cable.

- *dc current filtering reactance*. Each dc cable needs a reactance to avoid current interruption with minimum load, limit dc fault currents, and reduce current harmonics in the cable.
- *Capacitors or STATCOM for reactive power compensation*. As mentioned above, LCC converters require reactive power for proper operation. Capacitors or STATCOM are needed to compensate for reactive power demand in the grid.

2.3. HVDC VSC

High power IGBT development allows the use of VSCs in HVDC systems in the frequency range of 1–2 kHz [10,11] with much lower harmonic distortion than HVDC LCC systems although with higher power losses (4–5%). Today two manufacturers are able to build this HVDC VSC systems, Siemens and ABB. ABB uses the trade mark *HVDC light* [12] and Siemens *HVDC plus* [13]. Commercial systems are available with power between 50 and 1.100 MW with voltages up to ±300 kV. The first HVDC VSC System was installed in 1997 in Hellsjön by ABB, with a power rating of 3 MW and 10 kV voltage with the goal of studying the viability of the technology. During the last ten years several systems have been built, including submarine transmission lines. Unlike HVDC LCC, a VSC converter substation located in an offshore platform exists at the gas extraction platform of Troll, with rated power of 80 MW, transmission distance of 68 km and ±60 kV. Fig. 3 shows the schematic of a HVDC VSC transmission system.

HVDC VSC systems allow independent and total control of active and reactive power at each end of the line and power transmission can be controlled with high flexibility. At the offshore station reactive power can be supplied for the marine generators and at the onshore substation reactive power can be used to regulate voltage at the Common Coupling Point. Active power control can be used to regulate frequency in the grid, which can be very helpful if the grid onshore is weak. Even when no active power is available from the marine farm, the onshore station can operate as reactive power regulator to sustain the grid voltage. HVDC VSC converter stations are more compact than HVDC LCC and the offshore platform size can be smaller and less expensive.

VSC converters can start even with a dead grid, thus no additional start-up mechanism is necessary offshore. Even when the onshore grid has collapsed, the system may start by itself.

A HVDC VSC system has the following main components:

- Transformers.
- HVDC VSC converter substations (offshore and onshore).
- ac and dc filters.
- dc current filtering reactance.
- dc cable.

All filters and reactances in an HVDC VSC system are smaller than the equivalent HVDC LCC components because of the higher switching frequency of the converter and there is no need for reactive compensation because the converter is able to control reactive power.

Both offshore and onshore a transformer adapts the voltage level to the transmission line and a VSC converter on each side of the line makes the ac–dc conversion. The VSC converter is a three-phase IGBT inverter (multilevel converters are very well suited in this application for their high voltage capacity an lower harmonic content) operating at 1–2 kHz. Higher frequencies would reduce the filter size but switching power losses would be excessive.

As with HVDC LCC, various installation of power transmission between onshore grids exist (see Table 3). As already mentioned, a HVDC VSC station located offshore exists at the Troll gas platform in the North Sea.

HVDC VSC can also increase the flexibility of the generating technologies and the cost of the power converters if very high voltage (VHV) generators are used in the marine power generators. The HVDC VSC power converters could be directly used to power the generators in the marine farm as shown in Fig. 4. Series connected generators operating with input directly from the dc bus voltage would bring energy savings, drastic reduction of heat and power losses, and elimination of the transformer, although additional power electronics would be needed for balancing of the capacitor voltages.

However, conventional generators cannot be connected directly to very high voltage levels (limited to around 16 kV) needing a step-down transformer first to drop the voltage down from the dc bus voltage to an acceptable level. VHV generators have been developed from well-proven synchronous motor technology, incorporating new cables and winding technology on the motor stator that makes it possible to connect the motor directly to 60 kV or higher, and achieve smooth startups. Connecting an VHV generator to the HVDC VSC power converter results in a compact and lightweight electric drive systems and is

Table 3
Marine HVDCVSC installations

Project	Power (MW)	Transmission system (km)	Voltage (kV)
Cross Sound (U.S.A.)	330	40	150
Gotland Light (Sweden)	50	98	80
Tjaereborg Light (Denmark)	7.2	4.3	9
Troll A Gas Platform (Norway)	80	68	80

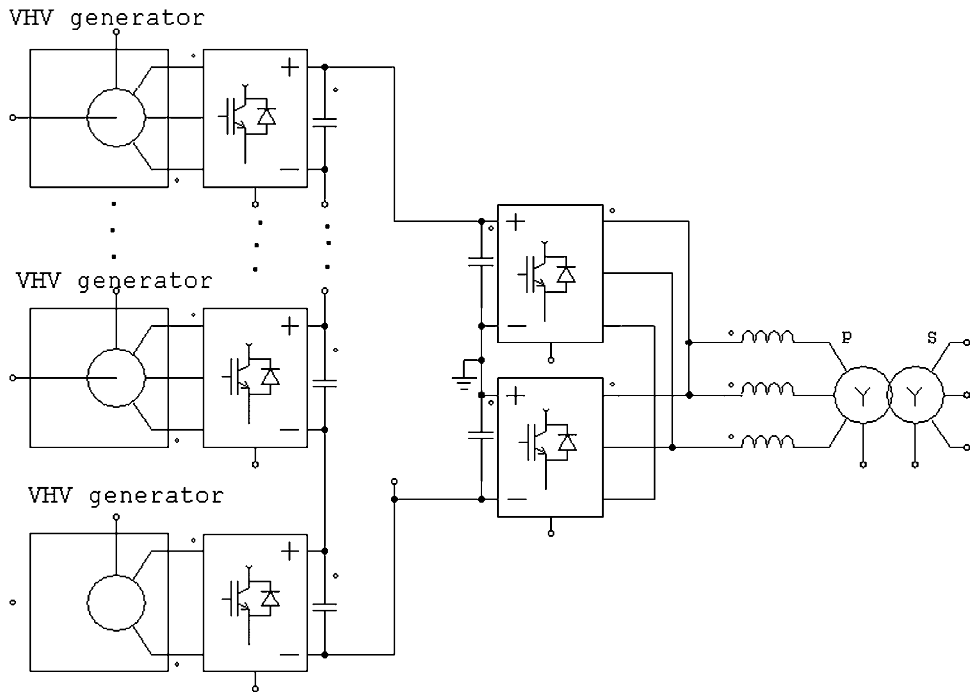

Fig. 4. Series connection of HVDC VSC.

also a transmission system, with clear advantages in space and weight saving offshore. Higher voltage also allows operation at lower current for the same power output. Today, this technology only exists for very high power motors (several tens of MW) from ABB, and the marine power generating devices have not been designed for such high power levels yet. The applicability of VHV generators to marine power generating systems could be a new field of research.

2.4. Hydrogen storage

A totally different approach is the generation of hydrogen in the offshore generators. The hydrogen can be stored in some type of floating tank or directly in a vessel and then transported onshore with some type of gas or liquid hydrogen tanker vessel. This alternative eliminates the need for an offshore transmission system and all the equipment for connecting the generators to the electrical grid. This would make the installation of marine power generation farms much cheaper. Anyway this alternative has two mayor drawbacks that make it impossible to deploy today.

First, the efficiency of the conversion of mechanical power to hydrogen, and then from hydrogen again to electrical energy is extremely low and a great boost in the efficiency chain should be achieved. In order to obtain hydrogen from electrical power the following losses must be accounted for, 30% losses for water make-up and electrolysis and 35% losses for compression of hydrogen. When converting hydrogen to electrical power the efficiency is 50% [14]. The cost reduction of the marine power system should be offset with the loss of benefits from the reduced efficiency.

Second, a market for hydrogen should exist. A realistic market could be the electrical vehicle but the efficiency would be very poor. For example the efficiency of vehicles with diesel propulsion is 25–33% when the whole energy chain is studied. If electric propulsion is used (without hydrogen storage), the efficiency is about 66% but when hydrogen is introduced in the electric chain the efficiency falls to 17% [14].

3. Submarine cables

One of the most important items in the design of a submarine transmission system is the choice of cable type. The type of cable directly affects the cost of the system and its installation. Tides and currents, soil stability, seismic activity and trawling and anchorage in the zone may be the determining factors when choosing the cable type in each installation. Today submarine high voltage cable manufacturers are found only in Europe and Japan. Some of the most important manufacturers are Pirelli (Prysmian), Sumitomo, ABB, Hitachi, and Nexans.

The structure of a submarine cable is as follows:

- *Conductor core*. The core carrying the current is a circular section formed with threaded wires. The core material in medium and high voltages is copper. Sometimes aluminum can be used but a bigger cross-sectional area is necessary. Current carrying capacity can be increased up to sections of 2000 mm^2. Bigger sections are very hard to bend and the folding radius becomes too large (5–6 m). The current carrying capacity depends on the line voltage, rated power, cable length, isolation method, burying depth, soil type and electrical losses. A good reference in this field is [15]. In HVAC transmission system it is advisable to join the three-phase cores in a single cable, and sometimes two cores are used in HVDC applications. By doing so, cable cost and installation costs are reduced and lower electromagnetic fields and induced current loss than using separate cables are obtained. The main disadvantage is that multicore cables require a bigger number of intermediate joints and they can be rated to lower power than separate cables. In dc cables, the path for current return may be the earth electrode water or even low voltage cables, thus saving one cable core, depending on the environmental regulation because some chemical reactions take place at the electrodes.
- *Electrical insulation*. Electrical insulation characterized by the material (oil impregnated paper or plastic) and the manufacturing method (paper sheets or extruded plastic). There are several long-distance submarine cable types. Historically, and up to now

Fig. 5. Submarine cable types: (a) LPFF cable (courtesy of ABB); (b) MI cable (courtesy of Prysmian); (c) three-core XLPE ac cables (courtesy of Prysmian); (d) one- and three-core XLPE dc cables (courtesy of Prysmian); (e) cable with optic fiber (courtesy of Sumitomo).

the most extended cable type is cellulose paper impregnated in synthetic or mineral oil. Oil impregnation can be of two types, low pressure oil filled (LPOF) and low pressure fluid filled (LPFF) where the core is covered by a hollow shaft where oil is circulated by pumps at both ends of the line (Fig. 5(a)). Installation and maintenance of the pumping system and the environmental danger of oil spill are a serious drawback in this type of cable. LPOF and LPFF can be built with transmission distances up to 50 km, longer distances are not possible because of the impracticability to maintain oil pressure. Another drawback is the need for cable protection when cable burial is necessary. This is a well-proven technology but better performing cables are being introduced in the market. Mass Impregnated (MI) cables are of similar construction, but the paper insulation is impregnated in resin and high viscosity oil and no oil circulation system is needed (Fig. 5(b)). This type of cable has been traditionally in HVDC transmission.

Cross-linked polyethylene cable (XLPE) is the most promising alternative cable in submarine cables (Fig. 5(c)). The insulation is made of solid dielectric, also known as extruded dielectric. The manufacturing process allows lower cost and longer distances than LPOF and LPFF. It has better bending capability, higher mechanical resistance and lower weight than other cables, thus the installation process is more easy. The absence of oil circulation requires less joints along the cable and there is no risk of oil spill. XLPE cables can carry nominal current with a cable temperature of 90 °C and it can withstand short-circuit currents with temperatures up to 250 °C. Nexans, a manufacturer from Norway, can deliver XLPE cables with voltages up to 420 kV. The problem of dc voltage breakdown of XLPE cables has been solved and it can be used in HVDC applications (Fig. 5(c)). Ethylene propylene rubber (EPR) cables are similar to XLPE cables but at higher voltage ratings they have higher capacitance [15].

- *Shield*. A conductor layer of paper or extruded polymer around the cable reduces electric field strength and field concentration zones. Also a better fixation of the insulation and the core is obtained.
- *Sheath*. In the outer face of the shield of each core a metallic sheath connected to earth for fault currents. This sheath is also a barrier for water. In ac cables the sheath carries induced currents and losses are generated. The only type of cable without a sheath is EPR.
- *Armature*. Cables are covered with an outer metallic armature that provides mechanical strength with anti corrosion protection. Sometimes a repellent is used to avoid damage by marine fauna. This armature is formed by galvanized steel wires.
- *Optic fiber*. Optic fiber can be inserted in the cable for communications, cable monitoring, etc. (Fig. 5(e)). In this case the temperature of the cable may be limited to avoid damage in the optic fiber.
- *Protecting sheath*. A final propylene sheath is used as the final outer protecting layer.

In ac applications the cable must carry the load current and the reactive current demanded by the cable capacitance. This

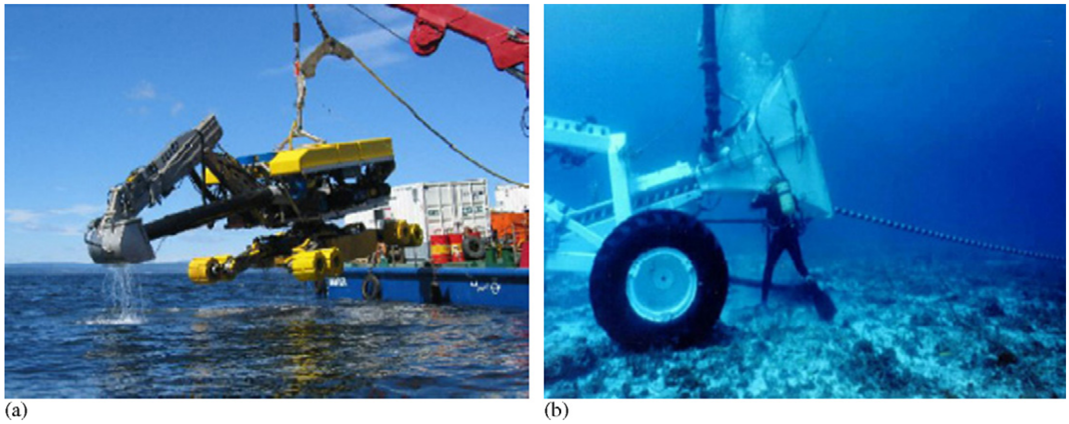

Fig. 6. Submarine trenchers: (a) Capjet (courtesy of Nexans); (b) Hydro-plow (courtesy of Prysmian).

reduces the power rating of the cable. Capacitive current is obtained as

$$I_c = 2\pi fCVL$$

where f is the system frequency, C the capacitance per km (0.2–0.3 μF/km), V the cable voltage and L is the cable length in km. Depending on system frequency and voltage capacitive currents between 10 and 25 A/km are generated.

The current carrying capacity of the cable, I_p, is

$$I_p^2 = I_t^2 - I_c^2$$

where I_t is the cable capacitive current. For short-transmission distances capacitive current is not excessive important, but for distances longer than 60–80 km capacitive current becomes equal to the load current.

Capacitance is a distributed parameter and capacitive current levels are different along the cable. Reactive Compensators are placed at both ends of the line offshore and on shore. The compensators obtain a more even distribution of the capacitive currents.

In HVDC applications there is no capacitive current because $f = 0$.

Losses in submarine cables are generated due to the following reasons:

- Dielectric losses. This type of loss is quite small.
- I^2R losses in the core. These are the most significant losses in submarine cables.
- I^2R losses in the metallic sheath, generated by induction of the main core current. This loss can be up to one third of the core losses.
- I^2R losses in the steel armature, also generated by induction of the main core current. This loss can be up to one third of the core losses as well.

The transmission distance of HVAC submarine cables are lower than overhead lines because the capacitance and circulating reactive currents are higher.

The performance of submarine cables is tested according to several standards [16–20].

3.1. Installation and maintenance

Installation of a submarine cable requires a thorough study of the seabed, currents, seismology, burying method, etc. Generally submarine cables are buried in the seabed to avoid damage by fishing nets or anchors. The cost of the installation can be higher then the cable itself. Specially built vessels and submarine trenching robots are necessary and there is a limited number available. The installing vessels must be able to carry huge drums containing the cable, cable tensioning machines and dynamic positioning systems for a very precise manouvre while installing the cable. The submarine trenchers must be able to operate on very difficult topographical areas and with a dredging capacity of 1–4 m. Today robots capable of operating at depths of 1000 m exist, such as Capjet of Nexans and Hydro-plow of Prysmian (Fig. 6). A water-jet system is used both to create a trench and to propel the trenching machine. These vehicles are used for trenching umbilicals, power cables and fiber-optic cables as well as pipelines. They fluidise the seabed material to create the trench, the fluidised material then falls back on top of the umbilical as back-filling after the machine has passed. The cable does not pass through the machine, and no forces are directly applied to it—therefore there is no risk of damage to it during the trenching process. The machines are capable of trenching in most clay and sandy soil conditions.

Each cable must be installed separately. ac cables must be placed close enough to avoid induced currents but not to close to avoid cable crossing during the installation process. On shore 1 m separation is enough but, under water, 20 m are necessary and induced current losses are higher. dc cables must be close enough to avoid generation of strong magnetic fields [21].

Cables along their length are divided and linked with repair joints for the repair and maintenance of submarine transmission and distribution systems capable of enduring the extremes of mechanical and electrical stresses encountered during system installation and operation.

Marine generations must have a very high reliability and availability and fault location must be carried out as fast as possible. The repair time of an onshore buried cable is more or less a week but a submarine cable may be much higher, specially if the vessels are not available or the weather is rough. In HVDC systems, the converter controllers can detect the faulty cable, but the exact location of the fault is necessary for the repair works. Precise detection of the fault location is obtained using high voltage pulse generators (thumpers) and time domain reflection meter (TDR) for measuring the travel time of the wave. More exact location is obtained with power pulse generators. The power pulse generates a flashover at the fault location. The sound of the flashover is measured using microphones.

3.2. Connecting cables and floating platforms

Many of the marine power technologies will require some type of connection between a floating device (generator, platform, ...)

and a cable lying in the seabed. This is a challenge for submarine cable manufacturers. The dynamic section of the cable is subject to substantial forces such as waves and current, and, in the case of a floater, the motions of the platform or vessel itself. The cable by itself is not ready to withstand this type of load, mainly because of the low fatigue resistance of the cable shield around the core.

In the oil and gas industry J-tube raisers are used to connect a platform, a buoy or a ship to a pipe or an installation on the sea bottom or to another floating platform, sometimes several hundred meters below the sea level. J-tubes are conduits extending from surface facilities down tower structure guide frames and exiting via long-radius bends to the seabed for later pull-in of flowlines, pipelines, umbilicals and cables. The experience in umbilicals in oil and gas industries may be very valuable in the development of new marine power generation systems. An umbilical is a long, flexible construction consisting of tubes, cables, armouring, fillers and wrapping contained within a protective sheath.

Other devices such as the *pulling head* and the *hang off* have been developed to ensure that torsionally balanced or unidirectionally armoured (coilable) cables safely reach their destination on or below the ocean floor such that the system can be connected and maintained with confidence. All these devices should have to be adapted for high voltage cabling.

3.3. Cost reduction in submarine cables

Several measures may reduce the cost of the cable system:

- Cables inside the marine power farm may not be buried if there is no risk of trawling by fishing nets or anchoring. Submarine cables have suffered a high number of accidents for these reasons but if adecuate signaling exists this danger is minimized inside the farm.
- The core material can be aluminum, thus reducing weight between 15 and 20% and cost by a factor of 6. Aluminum is affected by corrosion and a lead shield is necessary.
- A better understanding of the thermal behaviour of cables buried under the seabed may help reduce their size.
- Cables can be covered with a protective steel layer or using concrete instead of burying it.

All of the above proposals should be accompanied by a very thorough study of risks and benefits.

4. Offshore platforms

When the transmission system is above 33 kV *offshore* transformer station is needed in order to achieve the desired voltage level. In the case of HVDC systems, the power converters, dc inductors, filters and ancillary services also must be located offshore. The placement of a transformer station or HVDC converter in an offshore platform is a mayor problem and it increases the cost of the transmission system. The platform should also contain instrumentation, communication equipment, auxiliary diesel generator, fuel, fire prevention systems, hoists, etc. The location of the platform could be either above the sea level or submarine.

4.1. Submarine platforms

A submarine platform is conceptually interesting because, unlike floating platforms, it can be fixed to the seabed without moving parts and the cable connection is simplified. Submarine platform design requires not only that they are fit to operate reliably over the design lifetime, but also that they do not suffer damage from the forces they are exposed to during the installation process. Once installed, it is important that they do not suffer damage from other sea activities such as trawling or anchorage.

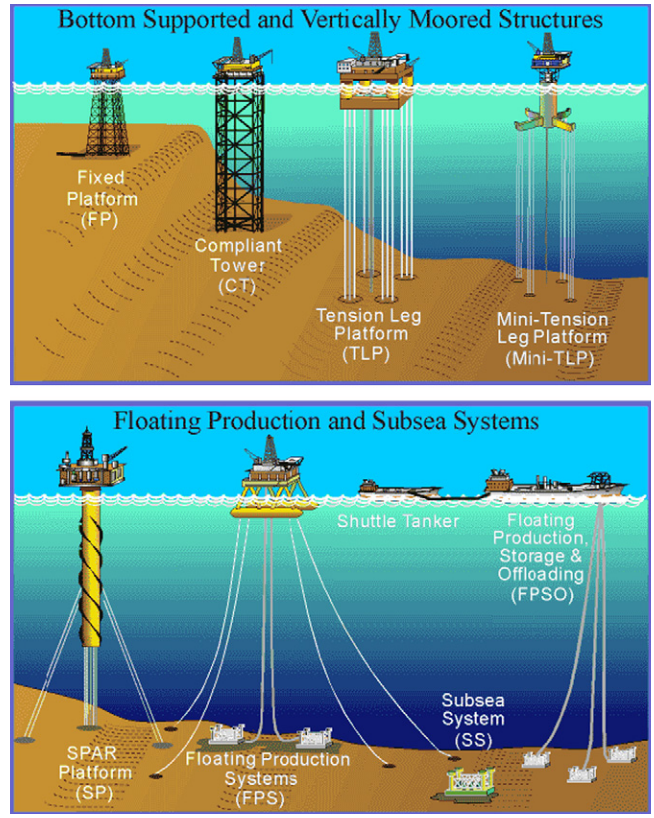

Fig. 7. Oil and gas platform types (courtesy of Energy Information Administration, Office of Oil and Gas).

Current technology is scarce, and only oil and gas extraction umbilical systems are able to place equipment at considerable water depth. This is an interesting option in HVAC systems where only passive components with little service needs are used. Prototypes are being built in the Wave Hub project [6].

It is very unlikely to place HVDC systems on the seabed because of the necessary maintenance.

4.2. Platforms above sea level

A second alternative, currently more realistic, is the placement of the platform above the sea level, either floating or fixed. The oil and gas industry are the main reference and some experience is being gained, mainly in low depth and fixed platforms, in the wind power industry. The most relevant platform types are shown in Fig. 7:

- *Fixed platforms* are built on concrete or steel towers on the seabed. Several construction types exist: steel jacket, concrete caisson (condeep concept), compliant tower, floating steel and floating concrete. The structure may be directly erected in the sea, or it can be built on the coast and then tugged to the final location. In the crude extraction industry fixed platforms are cost competitive with water depths of 520 m. In marine power applications the limit is not so deep because of the lower yield. In wind farms concrete caisson with a single pylon in Nysted (Fig. 8(a)) or with a tripod in Horns Rev (Fig. 8(b)).

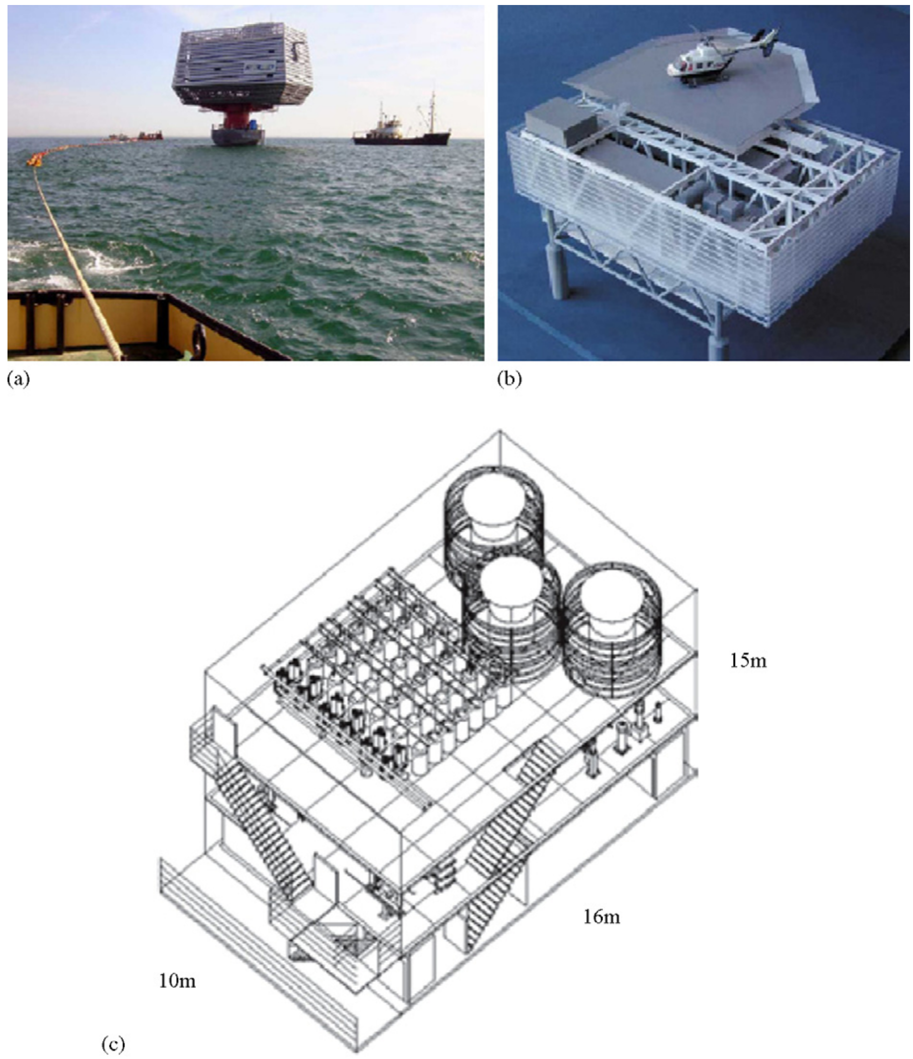

Fig. 8. Wind farm substation platforms: (a) Nysted (courtesy JD Contractor); (b) Horns Rev (courtesy Eltra); (c) Troll (courtesy ABB).

The Horns Rev 160 MW wind farm transformer substation has an area of 20 m × 28 m and it is located 14 m above the sea level. It contains a 36/150 kV transformer, 36 and 150 kV switchgear, instrumentation control and communications equipment, a diesel generator with 100-ton fuel, fire prevention system, a hoist, room for operators and a salvation boat.

The Troll 84 MW HVDC VSC station (Fig. 8(c)) has an area of 10 m × 16 m, 15 m height and a weight of 275 tons. The substation is placed on a huge gas extraction platform.

- *Floating platforms*. When the seabed is too deep, the only alternative is a floating platform. Designing floating platforms is challenging because oscilation, tether and torsion load are present in the connection of the submarine cables to the platform and in the fixing elements of the platform. Stability of the platform is obtained using a mix of the following three concepts: ballast, mooring lines or buoyancy [22]. Ballast stability is achieved by means of a heavy weight below the flotation line. Buoyancy is achieved by means of a very wide floating surface. Mooring lines provide stability by means of the tension in the chain. Several floating types can currently be found:
  - *Semi-submersible platforms*. Based on the buoyancy concept, the "legs" of the platform have high floatability to keep the platform above the sea level, but their weight is enough to keep the structure upright. They are floated to the final location and then tanks placed in the legs are filled with water until the desired position is obtained. They are placed in sea depths between 180 and 1800 m.
  - *Jack-up towers*. They work like the jack of a car. The structure is folded while it is tugged and then they unfold to be fixed to de sea bed. This method is only useful in shallow waters.
  - *Tension-leg platforms*. These platforms are fixed to the seabed with four tension-legs that remove almost completely any vertical displacement. They can be used with water depths of 2000 m. Their cost is low and they may be the most attractive alternative.
  - *Spar platforms*. The mooring lines are not tensioned and stability is achieved with a ballast below the flotation line. The first Spar platform is Neptune of the Kerr-McGee company. It is anchored at a depth of 588 m in the Gulf of Mexico. The deepest depth achieved with Spar platforms is 1710 m (Devil's Tower, Gulf of Mexico).
  - The oil and gas industry sometimes uses drillships. All the necessary extraction equipment is placed on a ship. It remains anchored in a fixed location until the well is exhausted or until its load capacity is full, then it moves to a new location. This can

Table 4
Cost of transformers as a function of rated power [24]

Rated power (MVA)	Cost (M€)
800	5.04
722	4.67
630	4.22
400	3.00
300	2.43
250	2.10
200	1.78
180	1.65
150	1.44
125	1.25
100	1.06
50	0.63
40	0.53

Table 5
Cost of reactive compensation

Rated power (MVA)	Cost (M€)
132 kV	
32.5	0.3033
65	0.5105
97.5	0.6923
130	0.8593
162.5	1.0162
195	1.1654
220 kV	
71	0.5455
142	0.9183
13	1.2453
284	1.5458
355	1.8279
400 kV	
226	1.3020
452	2.1916
678	2.9721
904	3.6892

be a very attractive alternative, specially during HVDC system development. It allows to deploy very fast an HVDC substation.

5. Cost of submarine transmission systems

It is not possible to provide the exact cost of submarine transmission system because of the multiple factors affecting each installations ant the secrecy of manufacturers. Anyway some essays to establish approximate values according to all available information have been tried. This section is based mainly in the conclusions obtained by Lazaridis [23].

5.1. Cost of HVAC systems

In HVAC systems the cost of the following components must be evaluated:

- *Transformers*. The cost of transformers is obtained as

  $$C_t = 0.003227P^{0.7513}\,\text{M€}$$

  where P is rated power in MVA [23].

  Table 4 shows estimated cost of transformers.
- *Reactive compensation*. Reactive power compensation depends on the transmission distance and voltage level of the line. The cost of reactive compensation equipment is about 2/3 the cost of a transformers of the same apparent power rating [25]. Using this criteria an approximation of the cost of reactive compensation is shown in Table 5 for different voltage levels.
- *Submarine cable*. According to Lundberg [25] three-core XLPE cable cost can be estimated as

  $$C_{132} = 1.5\,\text{M€/km for 132 kV cables;}$$

  $$C_{220} = 1.65\,\text{M€/km for 220 kV cables.}$$
- *Cable installation*. Assuming laying of a single cable for each ship trip, estimated cost is

  $$C_{\text{install}} = 100{,}000\,\text{€/km}.$$
- *Switch gear*. According to the model by [25], the switchgear system cost for four different voltage levels is shown in Table 6.

Table 6
Switchgear cost

Switchgear voltage (kV)	Cost (M€)
33	0.058
132	0.124
220	0.183
400	0.303

Table 7
Cost of HVDC LCC submarine cables

Cable rated power (MW)	Project	Final cost	Cost in 2004
600	SwePol link [26]	860.000 €/km (2002)	900.000 €/km
550	Iceland link [27]	820.000 $/km (1999)	724.000 €/km
500	ItalGre link [26]	660.000 €/km (2002)	700.000 €/km
440	Skagerrak 3 link [28]	170 M$ (1993)	700.000 €/km

5.2. Cost of HVDC LCC systems

The cost of submarine MI type HVDC cable and the cost of installation are shown in Table 7.

Extrapolating these costs, Lazaridis uses the following linear model of the cable and its installation [23]:

$$C = 1.148P + 156$$

where C is the cost of the cable in M€/km and P is the system rated power in MW.

Studies of burying the European grids within DGTREN program show that the cost of the latest HVDC LCC installations of HVDC LCC with submarine cable have had an approximated cost of 0.08 €/VA [29].

5.3. Cost of HVDC VSC systems

The cost of HVDC VSC is estimated based on values proposed by Lundberg [25]. The cost is defined as

$$C = 0.03066P + 0.0010388$$

where C is the cost in €/km and P is the rated power in MW.[2]

The installation cost is estimated as 200000 €/km.

According to HVDC VSC manufacturer ABB, the cost of the system is 0.11 €/VA [30]. According to the same report the cost of the Cross-Sound HVDC VSC transmission system (330 MW, 40 km and 150 kV) was 110 M€.

[2] Conversion of Swedish crown to euro according to currency exchange value on 12 November 2007.

5.4. Cost comparison

HVAC technolgy is the most economic alternative when reactive power is less than the active current in the line and losses in the line are limited within affordable limits. According to the previous assertions, in [23] HVAC systems are estimated to be cost effective for transmission distances up to 50 km. Consensus exist for this limit today in the scientific community [31].

According to Lazaridis [23] for higher transmission distance HVDC LCC are more cost effective than HVDC VSC and HVAC in offshore applications. The authors of this paper are sceptical about this assertion. The first HVDC system ever to be built in an offshore application has been a VSC system in the Troll gas platform. There are many reasons for this choice. First, all through this paper the technical benefits of HVDC VSC systems above HVAC and HVDC LCC have been clearly stated. The flexibility of the control of a VSC system will be a very important factor if marine power must provide a considerable proportion of the power of the grid. Second, previous studies of the cost of submarine transmission have not included the cost of the platform for the location of the converter substation offshore. The size of a VSC station is much smaller than the equivalent LCC station, thus the platform cost in VSC system us lower than in a LCC system and the advantage of cost of LCC versus VSC is not so clear.

Another factor is the evolution in component cost. The cost of HVAC equipment is not expected to be reduced (actually commodity prices are increasing due to the high demand of China and India and other factors). On the other hand, the cost of semiconductors (the main cost in HVDC stations) has a tendency to be reduced with time. According to Martander [32], the cost of HVDC system is mainly set by semiconductor cost and HVDC will be cost competitive with HVAC at any transmission distance in the year 2011.

6. Comparison of transmission systems

HVAC systems are widely used and established technology and they have lower cost than HVDC in short-transmission distances (distances shorten than 50 km, although this distance may be reduced soon). A mayor drawback of HVAC is the limited transmission distance. HVDC have no practical transmission distance limitation.

HVDC needs less cabling than equivalent HVAC. This generates a considerable cable and installation cost reduction, and the maintenance, environmental impact and fault rate are reduced in HVDC system.

HVDC (either LCC or VSC) have many technical advantages which can be very important if the contribution of marine power generation is expected to be a mayor player in the electrical energy generation and the grid stability. These advantages are

- HVDC cable loss is less than HVAC cable loss. This advantage is more significant in HVDC LCC because the converter losses are 1–2%. HVDC VSC systems have a power loss in the power converter of 4–5% which may offset the gain in the cables [33,34].
- Asynchronous connection of the marine farm and the grid. The frequency and phase of both receiving ends do not have to be synchronized because the dc link decouples both ends. Grid voltage dips and other faults have not a direct effect in the generators of the marine farm. There is more flexibility in the design of the generating units.
- HVDC allows almost instantaneous control of transmitted power and the system can contribute to the frequency control of the grid.
- HVDC VSC can control reactive power independently and voltage control is achieved. This is very helpful if the grid connection is weak.
- Unlike HVAC, HVDC does not increase the short-circuit current of the system.

It is obvious that the only reason (although one of the determining factors) for the use of HVAC is the lower cost at distances shorter than 50 km. This distance is being reduced with the cost of the silicon power switches. If environmental and stability criteria is also included in the choice of the system, HVDC can be a better choice.

Important differences exist between HVDC LCC and HVDC VSC:

- HVDC LCC requires an operating grid at both ends of the line. It is not able to start a collapsed grid. HVDC VSC systems are able to establish a grid from the dc voltage bus.
- HVDC LCC converters demand reactive power according to the thyristor firing angle. Reactive power compensation is necessary. HVDC VSC systems can control the reactive power at both ends and it can help in the control of the grid voltage [35,36].
- HVDC LCC has a switching frequency of 50–60 Hz and the necessary filters are very big. HVDC VSC systems have switching frequencies of 1–2 kHz, thus the necessary filter size is reduced.
- HVDC VSC power converter losses are 4–5% while HVDC LCC converter losses are 1–2%.

7. Conclusions

Current submarine HVAC power transmission is economically the best alternative with transmission distances shorter than 50 km. In the near future, semiconductor cost reduction and more stringent grid connection regulations will make HVDC VSC an alternative at distances shorter than 50 km.

At transmission distances longer than 50 km HVDC is cost competitive. Current research shows that HVDC LCC is more cost competitive than HVDC VSC but the size and weight of a typical HVDC station and complexity of control during startup have prohibited its use on offshore platforms. When the cost of the necessary offshore platform, the flexibility of the connection and CO_2taxation is included, HVDC VSC can be the best choice, and the first commercial HVDC transmission system to an offshore platform is a HVDC VSC system.

High power marine power generation farms will contribute significantly to frequency and voltage control of the grid if HVDC VSC systems are used.

New technologies must be developed in the following fields:

- Installation of submarine transformers and converters.
- Connection between high voltage static submarine cables and floating platforms or vessels.
- HVDC system cost reduction.
- Service free HVDC technology for submarine locations.
- Cable installation at seabed depths beyond 1000 m.
- Direct drive of very high voltage generators from the dc bus in HVDC VSC systems.

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References

[1] Chokhawala R, Maeland A. *Success of Troll-A HVDC light project is paving the way offshore*. Available online at: http://www02.abb.com/global/seitp/seitp161.nsf/0/52d334ee6698dca2c125712c0035f04b/file/Troll+application+is+Paving+the+way+Offshore.pdf.
[2] Trinnaman J. Survey of energy sources. Elsevier; 2004.
[3] Westwood A. Refocus marine renewable energy report. Elsevier; 2005.
[4] Jorgen CM. *Electrical power supply to offshore oil installations by high voltage direct current transmission*. Doctoral Thesis. Norwegian University of Science and Technology; 2001.
[5] *Deepwater victories. Oil Info*, no. 2; 2005.
[6] *Wave Hub project*. Available online at: http://download.southwestrda.org.uk/file.asp?File=/projects/general/wav-hub-briefing-note.pdf.
[7] Arrillaga J. High voltage direct current transmission. Institution of Electrical Engineers (IEE); 1998.
[8] Cartwright P, Xu L, Sasse C. Grid integration of large offshore wind farms using hybrid HVDC transmission. In: Proceedings of the Nordic wind power conference; 2004.
[9] *Areva*. Available online at: http://www.areva-td.com.
[10] Asplund G, Eriksson K, Svensson K. dc transmission based on voltage source converters. *CIGRE SC14 colloquium in South Africa*; 1997.
[11] Meier S. *Novel voltage source converter based HVDC transmission system for offshore wind farms*. Doctoral Thesis. Stockholm, Sweden: Royal Institute of Technology; 2005.
[12] *ABB*. Available online at: http://www.abb.com.
[13] *Siemens*. Available online at: http://www.ptd.siemens.de.
[14] Bossel U. Efficiency of hydrogen fuel cell, diesel-SOFC-hybrid and battery electric vehicles. Eur Fuel Cell Forum; 2003.
[15] Gilbertson OI. Electrical cables for power and signal transmission. Wiley; 2000.
[16] *Cigré, ELECTRA no. 171: recommendations for mechanical tests on sub-marine cables*.
[17] *Cigré technical brochure ref. no. 219: recommendations for testing dc extruded cable systems for power transmission at a rated voltage up to 250 kV*.
[18] *IEC 60228: conductors of insulated cables*.
[19] *IEC 60229: tests on cable over-sheats which have a special protective function and are applied by extrusion*.
[20] *IEC publication 141-1: tests on oil-filled and gaspressure cables and their accessories*.
[21] Wright SD, Rogers A, Manwell JF, Ellis A. Transmission options for offshore wind farms in the United States. In: *Proceedings of the AWEA annual conference*; 2002. p. 1–12.
[22] Butterfield S, Musial W, Jonkman J, Sclavounos P. Engineering challenges for floating offshore wind turbines. In: Offshore wind conference; 2005.
[23] Lazaridis LP. *Economic comparison of HVAC and HVDC solutions for large offshore wind farms under special consideration of reliability*. Master's thesis. Royal Institute of Technology, Stockholm; 2005.
[24] Ionescu A, Brkic S. *Report on the implementation of CBT mechanism in SEE region, ETSO, 4th Athens Forum*. Technical report; 2004. Available online at: http://www.seerecon.org/infrastructure/sectors/energy/documents/3ew/cbtmechanism_implementation.ppt.
[25] Lundberg S. *Configuration study of large wind parks*. Master's thesis. Chalmers University of Technology, Göteborg, Sweden; 2003.
[26] IFC Consulting. *Units costs of constructing new transmission assets at 380 kV within the European Union, Norway and Switzerland*. DGTREN/European Commission, Study Contract NoTREN/CC/03-2002, IFC Consulting Ltd., London, UK. Technical report; 2002.
[27] Cowhey T. *The Icelandic submarine cable*. Duke University, Fuqua School of Business; 2001. Available online at: http://faculty.fuqua.duke.edu/charvey/teaching/BA456_2001/ICE/ICEsolution.doc.
[28] Ilstad E. World record HVDC submarine cables. *Electrical Insulation Magazine, IEEE*; 1994. p. 64–7.
[29] Consulting I. *Overview of the potential for undergrounding the electricity networks in Europe*. DG TREN/European Commission, IFC Consulting Ltd., London, UK. Technical report. Study contract 2002/009/C2; 2003.
[30] *ABB. Middletown-Norwalk transmission project—technical description of VSC HVDC converter and cable technology*. Northeast Utilities, ABB Power Technologies AB, Ludvika, Sweden. Technical report; October 2004. Available online at: http://www.ct.gov/csc/lib/csc/docket_272/nh1–493072-v1-abb_technical_description.pdf.
[31] Green J, Bowen A, Fingersh LJ, Wan Y. Electrical collection and transmission systems for offshore wind power. In: *Offshore technology conference*; 2007.
[32] Martander O. *dc grids for wind farms*. Master's thesis. Chalmers University of Technology, Göteborg, Sweden; 2002.
[33] Todorovic J. *Losses evaluation of HVAC connection for large offshore wind farms*. Master's thesis. Department of Electrical Engineering, Royal Institute of Technology, Stockholm, Sweden; 2004.
[34] Barberis N. *Evaluation of losses of HVDC solutions for large offshore wind farms*. Master's thesis. Royal Institute of Technology, Stockholm, Sweden; 2005.
[35] Kirby N, Xu L, Luckett M, Siepmann W. HVDC transmission for large offshore wind farms. Power Eng J 2002;16(3):135–41.
[36] de Alegria IM, Andreu J, Martín JL, Ibañez P, Villate JL, Camblong H. Connection requirements for wind farms: a survey on technical requirements and regulation. *Renew Sust Energy Rev* 2007;11:1858–72.